

Optical microvariability properties of BALQSOs

Ravi Joshi^{1*}, Hum Chand¹, Alok C. Gupta¹ and Paul J. Wiita²

¹*Aryabhata Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital, 263129, India*

²*Department of Physics, The College of New Jersey, PO Box 7718, Ewing, NJ 08628, USA*

Accepted 2010 November 25. Received 2010 November 02; in original form 2010 September 07

ABSTRACT

We present optical light curves of 19 radio quiet (RQ) broad absorption line (BAL) QSOs and study their rapid variability characteristics. Systematic CCD observations, aided by a careful data analysis procedure, have allowed us to clearly detect any such microvariability exceeding 0.01–0.02 mag. Our observations cover a total of 13 nights (~ 72 hours) with each quasar monitored for about 4 hours on a given night. Our sample size is a factor of three larger than the number of radio-quiet BALQSOs previously searched for microvariability. We introduce a scaled F -test statistic for evaluating the presence of optical microvariability and demonstrate why it is generally preferable to the statistics usually employed for this purpose. Considering only unambiguous detections of microvariability we find that ~ 11 per cent of radio-quiet BALQSOs (two out of 19 sources) show microvariability for an individual observation length of about 4 hr. This new duty cycle of 11% is similar to the usual low microvariability fraction of normal RQQSOs with observation lengths similar to those of ours. This result provides support for models where radio-quiet BALQSO do not appear to be a special case of the RQQSOs in terms of their microvariability properties.

Key words: galaxies: active – galaxies: photometry – galaxies: jet – quasars: general

1 INTRODUCTION

Significant variability in brightness over a few minutes to several hours (less than a day) is commonly known as microvariability, intra-night optical variability (INOV) or intra-day variability. Optical microvariability is a well known property of radio-loud (RL) active galactic nuclei (AGN), particularly of its blazar subclass (e.g., Gupta et al. 2008 and references therein). Over past two decades there have been rather extensive searches for this phenomenon in blazars, other types of RLQSOs, and the far more numerous radio quiet quasars (RQQSOs) (e.g., Miller, Carini & Goodrich 1989; Carini et al. 1992, 2007; Gopal-Krishna et al. 1993b, 2000, 2003; de Diego et al. 1998; Romero, Cellone & Combi 1999; Sagar et al. 2004; Stalin et al. 2004; Montagni et al. 2006; Goyal et al. 2010). In the case of blazars these studies have provided useful constraints on the relativistic jet based models that are used to explain the origin of the large variations that help define the category (e.g., Marscher, Gear & Travis 1992; Rani et al. 2010). Since RQQSOs lack jets of significant power and extent, the microvariability seen in them may arise from processes on the accretion disc itself, and thus could possibly be used to probe the properties of the discs (e.g., Gopal-Krishna, Sagar & Wiita 1993a). How-

ever, so far there has been a lack of systematic effort to exploit microvariability properties to understand the nature of the substantial quasar sub-class with broad absorption lines (BALs), the BALQSOs.

These BALQSOs are AGN characterized by the presence of strong absorption troughs in their optical spectra. They constitute about 10–15 per cent of optically selected quasars (e.g., Reichard et al. 2003; Hewett & Foltz 2003). The BALs are attributed to material flowing outwards from the nucleus with velocities of 5000 to 50000 km s⁻¹ (Green et al. 2001). BALQSOs are classified mainly into two subclasses based on the material predominantly producing the BAL troughs. High ionization BAL quasars (HiBALs) have broad absorption from C IV, Si IV, N V and O IV lines. About 10 per cent of BALQSOs also show, along with HiBAL features, broad absorptions from lower ionization lines such as Mg II or Al III; these are called low-ionization BAL quasars (LoBALs). Any complete model of quasars and AGNs needs to explain self-consistently a wide range of their observational properties which also include: the presence of other emission/absorption lines, the fraction of quasars showing broad absorption lines and the fraction among them showing continuum variability such as microvariability.

Carini et al. (2007) have compiled a sample of 117 radio-quiet objects that have been searched for their microvariability. Of these, 47 are classified as Seyfert galaxies, 64 as QSOs, and 6 as BALQSOs. In their entire sample 21.4 per

* E-mail: ravi@aries.res.in (RJ); hum@aries.res.in (HC);
acgupta30@gmail.com (ACG); wiitap@tcnj.edu (PJW)

cent of the objects were found to exhibit microvariability, but among objects classified as Seyfert galaxies, QSOs and BALQSOs, microvariability was seen in 17 per cent, 23 per cent and 50 per cent, respectively (Carini et al. 2007). In addition, Rabbette et al. (1998) have noted that two radio-quiet BALQSOs displayed short term X-ray variability. The observed high fraction of microvariations in BALQSOs suggests that it might be worthwhile to expend more of the observing time devoted to microvariability on the BALQSO class if one wants to understand physical processes in or near the accretion disc. Clearly, the present sample size of BALQSOs is very small compared to those of the non-BALQSO classes, and no useful conclusions about their nature can be drawn from them. Therefore it is important to increase the sample of BALQSOs, so as to be able to arrive at firmer conclusions about the fraction showing microvariability. We note that if BALQSOs do really show a substantially higher duty cycle for microvariability than do non-BAL RQQSOs, this would shed light on the question of whether or not radio-quiet BALQSOs are special cases of the RQQSOs, especially in terms of their microvariability properties. For instance, if even weak jets dominate the rapid variability (e.g., Gopal-Krishna et al. 2003) then a higher duty cycle for microvariability will give indirect support for the hypothesis that BALQSOs are viewed at angles nearly perpendicular to their accretion discs (e.g., Ghosh & Punsly 2007). This is because jet fluctuations originating in relativistic jets pointing close to our line-of-sight are amplified in magnitude and compressed in timescale (e.g., Gopal-Krishna et al. 2003). Whereas, if BALQSOs show only the usual low microvariability duty cycles of normal RQQSOs (around 20 per cent) and the fluctuations still arise in weak jets, that would provide indirect support for alternative models, such as those where the BAL outflows come out closer to the disc plane (e.g., Elvis 2000). In conjunction with X-ray and optical spectral properties, such variation information is very useful in constraining various physical models for the origin of microvariability (e.g., Czerny et al. 2008) and the nature of BALQSOs itself (e.g., Weymann et al. 1991; Elvis et al. 2000). To address these questions, we have recently started a pilot program to make an extensive search for optical microvariability of BALQSOs.

This paper is organized as follows. In Section 2 we describe the main aspects of our sample selection criteria, while Section 3 briefly describes our observations and the data reductions. In Sections 4 and 5 we present our analysis and results, respectively. Section 6 gives a discussion and our conclusions.

2 SOURCE SELECTION CRITERIA

Our sample is chosen from the BALQSO catalogues compiled by Trump et al. (2006), Scaringi et al. (2009) and Gibson et al. (2009) which are based on Sloan Digital Sky Survey (SDSS) Data Releases 3 and 5 (DR3: Schneider et al. 2005; DR5: Adelman-McCarthy et al. 2007; Schneider et al. 2007). In addition, we also included one brighter BALQSO from the compilation by Weymann et al. (1991). Most of the sources were selected in such a way that both optical and X-ray spectral data are available for them in archives. All were at declinations that allowed for the observations to be made

at relatively low air masses. We also required our candidate sources to have $g_i \leq 17$. This constraint means that even with a 1-m class telescope we could obtain a good enough signal to noise ratio to detect fluctuations of < 0.02 mag with a reasonably good time resolution of < 10 minutes. We also limit the BALQSOs to have absolute magnitudes $M_i < -24.5$, so that the flux contribution from the host galaxy can be assumed to be negligible (Miller et al. 1990).

Our final sample consists of a total of 19 BALQSOs, as listed in Table 1. Among these BALQSOs 8 are classified as HiBALs, 10 are LoBALs and 1 is a mini BAL. The whole sample covers a redshift range of $0.39 < z_{em} < 2.9$.

3 OBSERVATIONS AND DATA REDUCTIONS

3.1 Photometric observations

Our observations of each of the BALQSOs were carried out continuously for ~ 4 h in the R passband, mainly using the 1.04-m Sampurnanand telescope located at the Aryabhata Research Institute of observational sciences (ARIES), Nainital, India. It has Ritchey-Chretien (RC) optics with a $f/13$ beam and is equipped with a cryogenically cooled CCD detector with a $2048 \text{ pixel} \times 2048 \text{ pixel}$ chip mounted at the Cassegrain focus (Sagar 1999). The readout noise of the CCD chip is $5.3 \text{ e}^-/\text{pixel}$ and it has a gain of $10 \text{ e}^-/\text{Analog to Digital Unit (ADU)}$. Each pixel of the CCD chip has a dimension of $24 \mu\text{m}^2$, corresponding to 0.37 arcsec^2 on the sky, and so covers a total field of $\sim 13' \times 13'$. To improve the signal to noise ratio, observations were carried out in a $2 \text{ pixel} \times 2 \text{ pixel}$ binning mode. The typical seeing during our observing runs at ARIES was $\sim 3''$. In addition, two sources were observed with 2.01-m Himalayan Chandra Telescope (HCT) located at the Indian Astronomical Observatory (IAO), Hanle, India. It is also of the RC design with a $f/9$ beam at the Cassegrain focus¹. The detector was a cryogenically cooled 2048×4096 chip, of which the central 2048×2048 pixels were used. The pixel size is $15 \mu\text{m}^2$ so that the image scale of $0.29 \text{ arcsec/pixel}$ covers an area of about $10' \times 10'$ on the sky. The readout noise of this CCD is $4.87 \text{ e}^-/\text{pixel}$ and the gain is $1.22 \text{ e}^-/\text{ADU}$. The CCD was used in an unbinned mode. The typical seeing during our observations at IAO was $\sim 1.5''$.

We chose an R filter for this observational program because it is at the maximum response of the CCD system; thus the time resolution achievable for each object is maximized. As most of our sources have $g_i \sim 16 - 17$, the best time resolution we could achieve was of the order of 3 minutes, and we almost always managed data points spaced less than 8 minutes apart, so very rapid fluctuations could be picked up. We also took care to select sources and fields of view so as to ensure availability of at least two, but usually more, comparison stars on the CCD frame that were within around 1 mag of the QSO's brightness. This allowed us to identify and discount any comparison star which itself varied during a given night and hence ensured reliable differential photometry of the QSO. Observations were made on a total of 13 nights for this program during December 2009 – June 2010, as specified in Table 1.

¹ <http://www.iia.res.in/~iao>

Table 1. Properties of the observed BALQSOs.

Object ^a	$\alpha_{2000.0}$	$\delta_{2000.0}$	g_i	M_i	z_{em}	R^b	Type ^c	Ref ^d	Date of Obs
WFM91 0226–1024	02 ^h 28 ^m 39.20 ^s	–10 ^h 11 ^m 10.0 ^s	15.16 [*]	–30.7 [*]	2.256	0.38	HiBAL	3	22.12.2009
J073739.96+384413.2	07 ^h 37 ^m 39.96 ^s	+38 ^h 44 ^m 13.2 ^s	16.99	–28.04	1.399	ND	LoBAL	1	22.12.2009
J084044.41+363327.8	08 ^h 40 ^m 44.41 ^s	+36 ^h 33 ^m 27.8 ^s	16.59	–28.36	1.225	0.66	LoBAL	1	06.01.2010
J084538.66+342043.6	08 ^h 45 ^m 38.66 ^s	+34 ^h 20 ^m 43.6 ^s	16.96	–29.03	2.149	ND	HiBAL	1	07.01.2010
J090924.01+000211.0	09 ^h 09 ^m 24.01 ^s	+00 ^h 02 ^m 11.0 ^s	16.68	–29.12	1.864	ND	HiBAL	4	25.01.2010
J094443.13+062507.4	09 ^h 44 ^m 43.13 ^s	+06 ^h 25 ^m 07.4 ^s	16.25	–27.40	0.695	0.14	LoBAL	1	16.02.2010
J094941.10+295519.2	09 ^h 49 ^m 41.10 ^s	+29 ^h 55 ^m 19.0 ^s	16.04	–28.56	1.665	ND	HiBAL	2	07.01.2010
J100711.81+053208.9	10 ^h 07 ^m 11.81 ^s	+05 ^h 32 ^m 08.9 ^s	16.21	–29.71	2.143	ND	HiBAL	1	25.03.2010
J111816.95+074558.1	11 ^h 18 ^m 16.95 ^s	+07 ^h 45 ^m 58.1 ^s	16.27	–29.34	1.735	ND	MiBAL	4	25.01.2010
J112320.73+013747.4	11 ^h 23 ^m 20.70 ^s	+01 ^h 37 ^m 47.0 ^s	15.84	–29.32	2.130	ND	LoBAL	2	17.01.2010
J120051.52+350831.6	12 ^h 00 ^m 51.52 ^s	+35 ^h 08 ^m 31.6 ^s	16.79	–28.77	1.717	0.23	HiBAL	1	12.05.2010
J120924.07+103612.0	12 ^h 09 ^m 24.07 ^s	+10 ^h 36 ^m 12.0 ^s	16.53	–25.69	0.394	0.33	LoBAL	1	08.05.2010
J123820.19+175039.1	12 ^h 38 ^m 20.19 ^s	+17 ^h 50 ^m 39.1 ^s	16.86	–25.99	0.449	1.03	LoBAL	2	09.05.2010
J125659.92+042734.3	12 ^h 56 ^m 59.90 ^s	+04 ^h 27 ^m 34.0 ^s	15.80	–28.19	1.025	ND	LoBAL	2	16.02.2010
J151113.84+490557.4†	15 ^h 11 ^m 13.84 ^s	+49 ^h 05 ^m 57.4 ^s	16.49	–28.37	1.359	0.91	LoBAL	1	23.04.2010
J152350.42+391405.2†	15 ^h 23 ^m 50.42 ^s	+39 ^h 14 ^m 05.2 ^s	16.68	–26.77	0.661	1.01	LoBAL	1	24.04.2010
J152553.89+513649.1	15 ^h 25 ^m 53.89 ^s	+51 ^h 36 ^m 49.1 ^s	16.85	–30.03	2.882	ND	HiBAL	1	12.05.2010
J154359.44+535903.2	15 ^h 43 ^m 59.44 ^s	+53 ^h 59 ^m 03.2 ^s	17.03	–29.28	2.370	ND	HiBAL	1	09.05.2010
J160207.68+380743.0	16 ^h 02 ^m 07.70 ^s	+38 ^h 07 ^m 43.1 ^s	16.10	–28.62	1.594	ND	LoBAL	1	14.06.2010

^a Sources marked with † were observed from the 2.01-m Himalayan Chandra Telescope (HCT), the others from the ARIES 1.04-m telescope.

^{*} Apparent R_{mag} and absolute magnitude are taken from Veron-Cetty & Veron (2006).

^b Ratio of the radio [5 GHz] flux to the optical [2500Å] flux taken from SDSS DR7 (Schneider et al. 2010); ND means no radio detection.

^c BAL type: for HiBAL, LoBAL see text; MiBAL = Mini Broad Absorption Line Quasar.

^d References: (1) Gibson et al. (2009); (2) Scaringi et al. (2009); (3) Weymann et al. (1991); (4) Trump et al. (2006)

Table 2. Properties of the comparison stars.

Object ^a	Star1(S1)		Star2(S2)		Q	R(mag)	S2	Q-S1	$\delta(V-R)$	S1-S2
(1)	$\alpha_{2000.0}$	$\delta_{2000.0}$	$\alpha_{2000.0}$	$\delta_{2000.0}$	(6)	S1	(8)	(9)	(10)	(11)
WFM91 0226–1024*	02 ^h 28 ^m 31.17 ^s	–10 ^h 17 ^m 15.4 ^s	02 ^h 28 ^m 40.65 ^s	–10 ^h 15 ^m 50.3 ^s	16.30	—	—	—	—	—
J073739.96+384413.2	07 ^h 37 ^m 22.23 ^s	+38 ^h 48 ^m 55.5 ^s	07 ^h 37 ^m 24.63 ^s	+38 ^h 41 ^m 29.5 ^s	17.00	15.68	16.81	–0.01	–0.74	–0.73
J084044.41+363327.8	08 ^h 40 ^m 21.03 ^s	+36 ^h 37 ^m 26.6 ^s	08 ^h 40 ^m 32.32 ^s	+36 ^h 33 ^m 34.5 ^s	16.59	16.32	16.17	+0.02	–0.12	–0.14
J084538.66+342043.6	08 ^h 45 ^m 42.98 ^s	+34 ^h 17 ^m 46.3 ^s	08 ^h 45 ^m 45.14 ^s	+34 ^h 17 ^m 07.3 ^s	16.95	16.05	16.66	–0.53	–1.20	–0.67
J090924.01+000211.0	09 ^h 09 ^m 17.27 ^s	+00 ^h 04 ^m 01.3 ^s	09 ^h 09 ^m 13.86 ^s	–00 ^h 01 ^m 24.6 ^s	16.67	15.66	16.52	–0.82	–0.39	+0.43
J094443.13+062507.4	09 ^h 44 ^m 40.39 ^s	+06 ^h 28 ^m 14.9 ^s	09 ^h 44 ^m 34.10 ^s	+06 ^h 30 ^m 33.0 ^s	16.24	15.62	16.76	–0.32	–1.19	–0.87
J094941.10+295519.2	09 ^h 49 ^m 23.32 ^s	+29 ^h 54 ^m 13.5 ^s	09 ^h 49 ^m 42.06 ^s	+30 ^h 01 ^m 07.1 ^s	16.06	15.80	15.44	–0.79	–0.93	–0.14
J100711.81+053208.9	10 ^h 07 ^m 17.82 ^s	+05 ^h 37 ^m 05.1 ^s	10 ^h 07 ^m 03.42 ^s	+05 ^h 34 ^m 07.0 ^s	16.27	15.37	14.55	–0.18	–0.47	–0.29
J111816.95+074558.1	11 ^h 18 ^m 13.91 ^s	+07 ^h 46 ^m 28.7 ^s	11 ^h 18 ^m 05.79 ^s	+07 ^h 51 ^m 21.5 ^s	16.15	15.94	15.59	–1.17	–0.49	+0.68
J112320.73+013747.4	11 ^h 23 ^m 21.59 ^s	+01 ^h 45 ^m 10.2 ^s	11 ^h 23 ^m 30.68 ^s	+01 ^h 49 ^m 55.6 ^s	15.84	15.98	15.67	–0.23	–0.57	–0.34
J120051.52+350831.6	12 ^h 01 ^m 13.18 ^s	+35 ^h 09 ^m 03.9 ^s	12 ^h 01 ^m 21.41 ^s	+35 ^h 04 ^m 18.7 ^s	16.79	15.26	15.12	–0.40	–0.26	+0.14
J120924.07+103612.0	12 ^h 09 ^m 07.90 ^s	+10 ^h 34 ^m 14.0 ^s	12 ^h 09 ^m 16.06 ^s	+10 ^h 38 ^m 38.0 ^s	16.50	15.82	15.07	–0.66	–1.08	–0.42
J123820.19+175039.1	12 ^h 38 ^m 47.21 ^s	+17 ^h 56 ^m 01.7 ^s	12 ^h 38 ^m 19.22 ^s	+17 ^h 46 ^m 07.9 ^s	16.42	15.62	15.15	–1.16	–0.27	+0.89
J125659.92+042734.3	12 ^h 56 ^m 47.73 ^s	+04 ^h 25 ^m 25.1 ^s	12 ^h 56 ^m 59.64 ^s	+04 ^h 31 ^m 49.3 ^s	16.04	15.13	14.85	–0.34	–0.32	–0.02
J151113.84+490557.4	15 ^h 11 ^m 06.35 ^s	+49 ^h 08 ^m 07.8 ^s	15 ^h 11 ^m 34.13 ^s	+49 ^h 07 ^m 17.0 ^s	16.49	16.07	16.12	–0.74	–0.19	+0.55
J152350.42+391405.2	15 ^h 23 ^m 59.73 ^s	+39 ^h 17 ^m 05.9 ^s	15 ^h 23 ^m 51.32 ^s	+39 ^h 11 ^m 48.4 ^s	16.65	16.35	15.64	–1.01	–0.11	+0.90
J152553.89+513649.1	15 ^h 25 ^m 57.63 ^s	+51 ^h 34 ^m 51.9 ^s	15 ^h 26 ^m 10.32 ^s	+51 ^h 36 ^m 11.1 ^s	16.84	16.78	15.75	–1.03	–0.28	+0.75
J154359.44+535903.2	15 ^h 44 ^m 29.09 ^s	+53 ^h 58 ^m 16.5 ^s	15 ^h 44 ^m 19.22 ^s	+53 ^h 58 ^m 03.2 ^s	17.05	16.48	16.06	–0.40	–0.48	–0.08
J160207.68+380743.0	16 ^h 01 ^m 34.59 ^s	+38 ^h 09 ^m 31.4 ^s	16 ^h 01 ^m 33.19 ^s	+38 ^h 05 ^m 14.2 ^s	16.83	15.66	16.16	–0.47	–0.34	+0.13

^a * This source is not in SDSS so good information about its color is not available.

3.2 Data Reduction

The raw photometric data was first pre-processed using standard routines in the Image Reduction and Analysis Fa-

cility² (IRAF) software. We generated a master bias frame for the observing night by taking the median of all bias

² IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

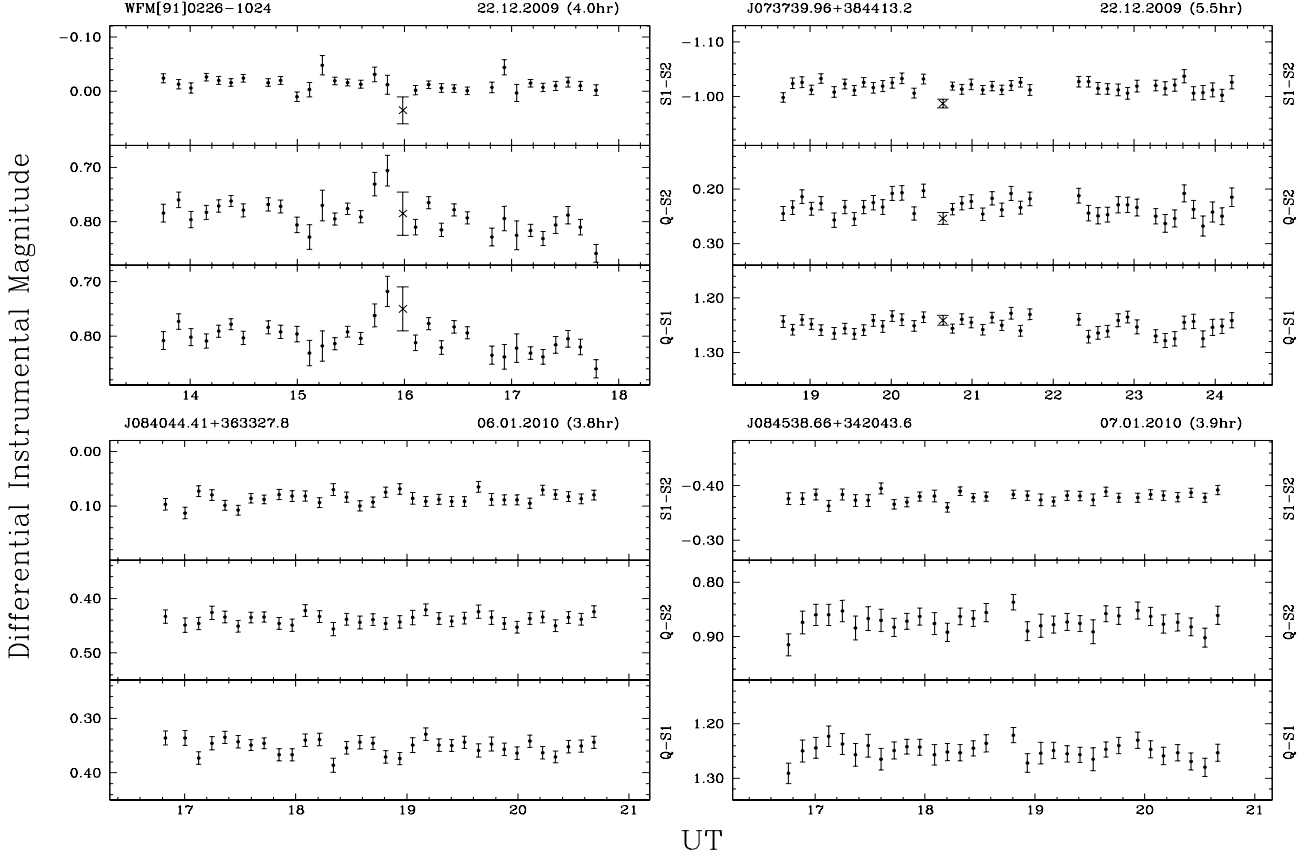


Figure 1. Differential light curves (DLCs) for the first four BALQSOs in our sample. The name of the quasar and the date and duration of the observation are given at the top of each night’s data. The upper panel gives the comparison star-star DLC and the subsequent lower panels give the quasar-star DLCs, as defined in the labels on the right side. Any likely outliers (at $> 3\sigma$) in the star-star DLCs are marked with crosses, and those data are not used in our final analysis.

frames taken on that night. This master bias frame was subtracted from all the twilight sky flat image frames as well as from the source image frames taken on that night. The routine step of dark frame subtraction was not performed because the CCDs used in our observations were cryogenically cooled to -120°C ; at that temperature the amount of thermal charge deposition is negligible for our brief exposure times. Then the master flat was generated by median combining of several flat frames (usually more than 5 taken on the twilight sky) in that passband. Next, the normalized master flat was generated. Each source image frame was flat-fielded by dividing by the normalized master flat in the respective band to remove pixel-to-pixel inhomogeneities. Finally, cosmic ray removal was done from all source image frames using the task *cosmicrays* in IRAF.

3.3 Photometry

The instrumental magnitudes of the comparison stars and the target source are obtained from the data by using Dominion Astronomical Observatory Photometry (DAOPHOT II) software to perform the concentric circular aperture photometric technique (Stetson 1987, 1992). Aperture photometry was carried out with four aperture radii, to wit, $\sim 1\times\text{FWHM}$, $2\times\text{FWHM}$, $3\times\text{FWHM}$ and $4\times\text{FWHM}$. Utmost

caution has been taken to deal with the seeing, and we have taken the mean full width at half maximum (FWHM) of 5 fairly bright stars on each CCD frame in order to choose the apertures for the photometry of that individual frame. The data reduced with different aperture radii were found to be in good agreement. However, it was noticed that the best S/N was almost always obtained with aperture radii of $2\times\text{FWHM}$, so we adopted that aperture for our final analysis.

4 ANALYSIS

4.1 Selection of comparison stars

The comparison stars are chosen on the basis of their proximity in both location and magnitude to the quasar. Preference was given to those stars having magnitudes similar to that of the monitored quasar, so that the errors in the Differential Light Curves (DLCs) will not be dominated by any faint object (see Sect. 4.2). The locations of the two best comparison stars for each BALQSO are given in columns 2–5 of Table 2.

In addition, our atmosphere acts like a colour filter of variable transparency, so the photometry of two stars (or

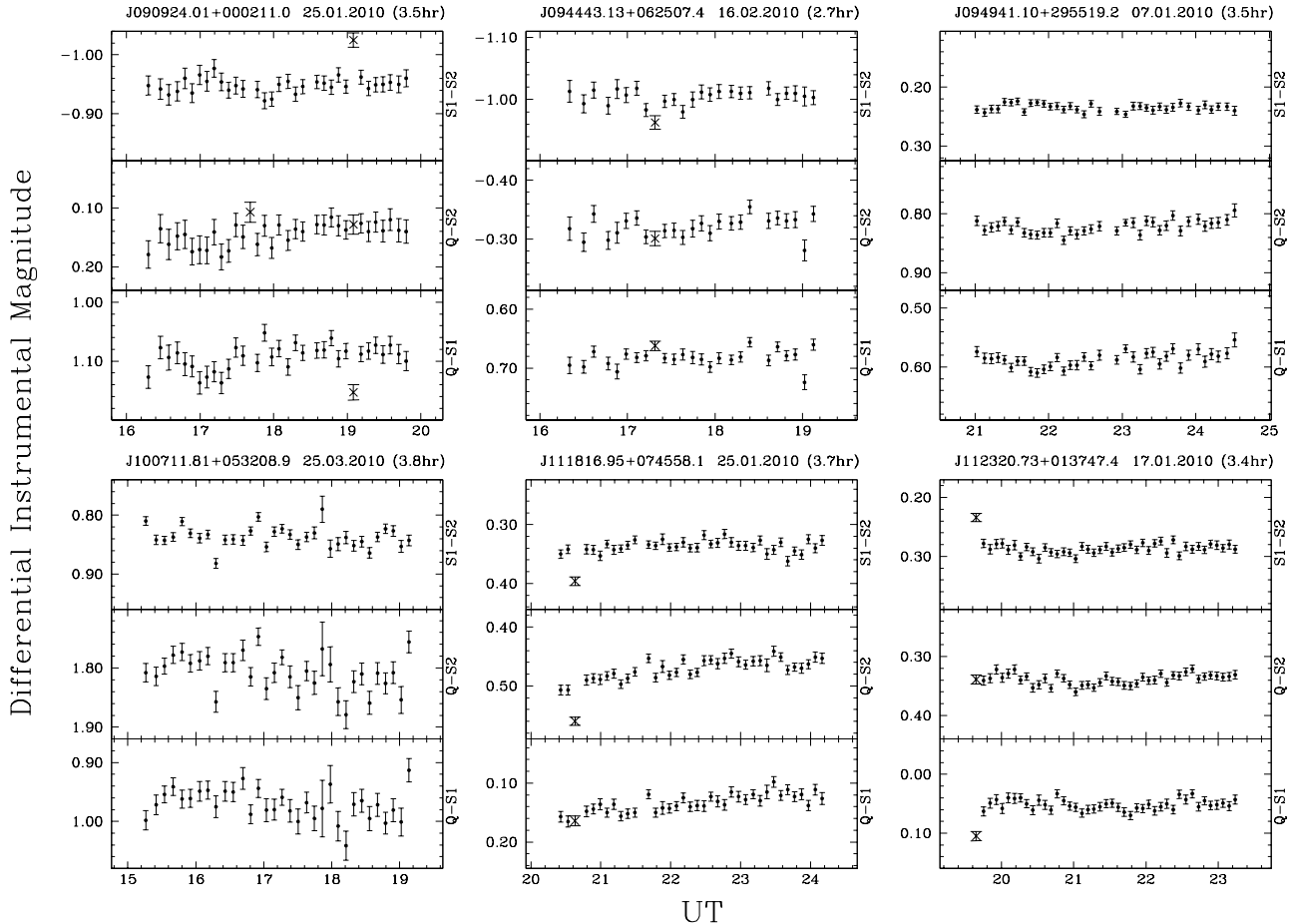


Figure 2. As in Fig. 1 for 6 more BALQSOs.

quasar-star pair) of different colours will be affected by different amounts because of the changing air-mass during the monitoring (e.g., Eq. 2, in Stalin et al. 2004). Therefore, for ascertaining the variability properties from DLC, the colours of the two objects in the DLC really should be similar. We list $V-R$ colour differences for all pairs of objects we observe in columns 9–11 of Table 2. For most of the quasar-star pairs the $V-R$ colour differences are smaller than unity, except for seven pairs (out of a total of 38) where the differences are the range of 1.0–1.20. Similarly, for the star-star pairs, the colour differences for all pairs are smaller than unity. Stalin et al. (2004) report a detailed investigation quantifying the effect of colour differences, and they show that the effect of colour differences of this amount on DLCs will be negligible for a specific band (see also Carini et al. 1992).

We also used the star-star DLCs to identify any spikes in them (unusually sharp rise or fall of the DLC over a single time bin), assuming that the true star-star DLC is overall non-variable or at worst reflects small stellar oscillations. Such spikes may arise from improper removal of cosmic rays, cirrus clouds or some unknown instrumental cause. Such outliers can sometimes significantly alter the nominal statistics on short-term variations, especially when DLCs do not have enough data points. We typically have ~ 30 individual temporal data points in our sample; see Table 3,

column 2. We removed such outliers if they were more than 3σ from the mean, by applying a mean clip algorithm on the comparison star-star DLCs. In cases where we find any such outliers we have censored those time bin data points from our analysis of quasar-star DLCs as well. Only DLCs once freed from any such outliers have been used for carrying out our statistical analysis of microvariability. However, we should stress that such outliers in our comparison star-star DLCs were usually not present and never exceeded two data points.

4.2 Statistics to quantify microvariations

4.2.1 C -test statistics

To quantify microvariation of a DLC, by far the most commonly used statistic is the so-called C -statistic (e.g., Jang & Miller 1995; Romero et al. 1999). This technique uses a variability parameter C , which is an average of $C1$ and $C2$ with

$$C1 = \frac{\sqrt{\text{Var}(q - s1)}}{\sqrt{\text{Var}(s1 - s2)}} \quad \text{and} \quad C2 = \frac{\sqrt{\text{Var}(q - s2)}}{\sqrt{\text{Var}(s1 - s2)}}. \quad (1)$$

Here $\text{Var}(q - s1)$, $\text{Var}(q - s2)$ and $\text{Var}(s1 - s2)$ are the variance of observational scatters of the differential in-

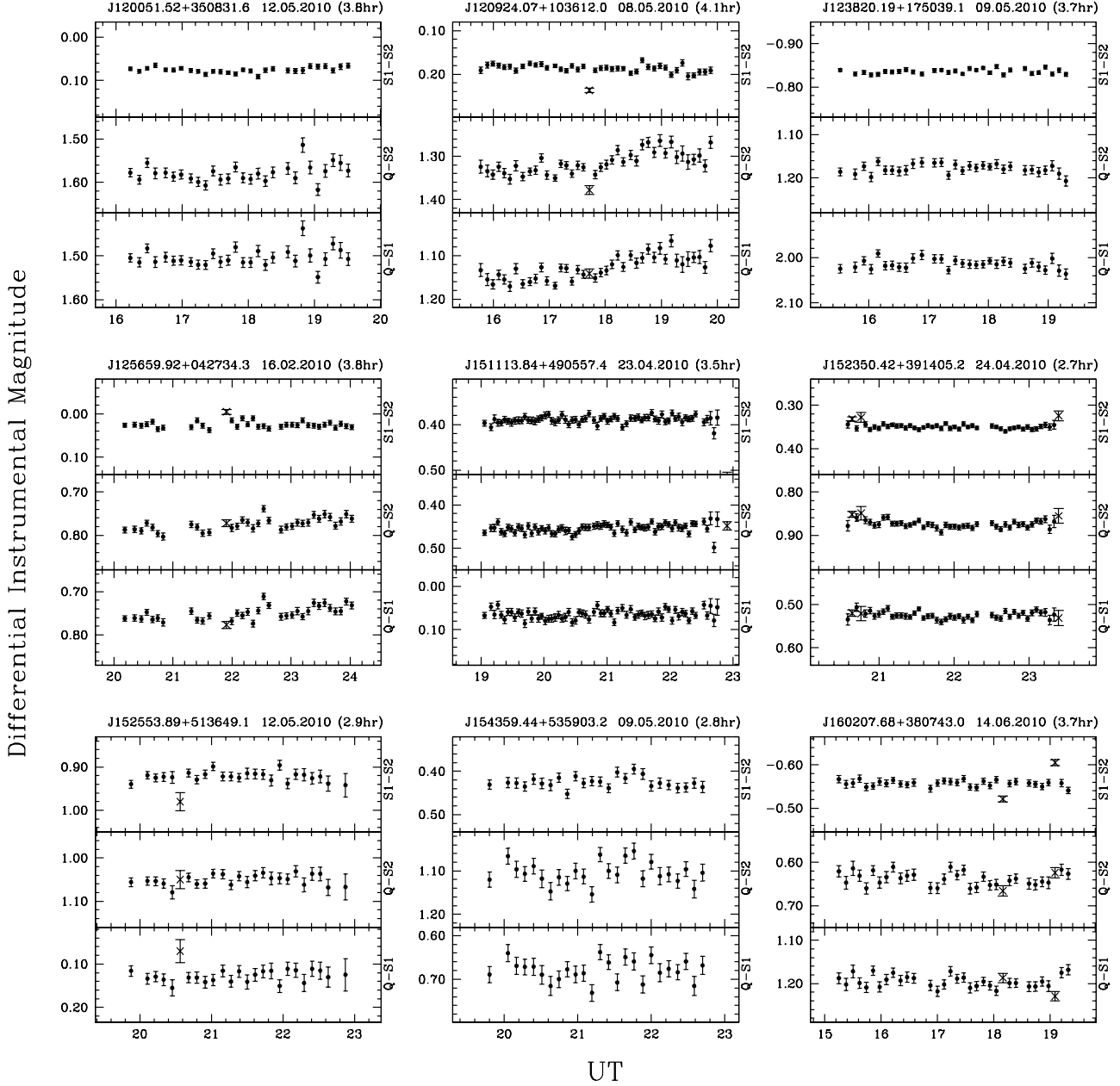


Figure 3. As in Fig. 1 for our last 9 BALQSOs.

strumental magnitudes of the quasar–star1, quasar–s2 and star1–star2, respectively. The normally adopted criterion to claim that variability is present is $C \geq 2.576$, which corresponds to a nominal confidence level of ≥ 0.99 .

4.2.2 *F-test statistics*

Despite the very common use of these C -statistics, de Diego (2010) has pointed out it has severe problems. Because it considers the ratio of two standard deviations rather than of variances it does not describe a normally distributed vari-

able and it is not properly centered with the mean expected value being zero; hence it is not a good statistic and de Diego (2010) concludes that the nominal critical value for the presence of variability (i.e., 2.576) is usually too conservative.

Another statistical method that can be used to quantify the presence of microvariability is the F -test, which has been recently been shown to be a more powerful and reliable tool for detecting microvariability (de Diego 2010). The F value is computed as

$$F_1 = \frac{\text{Var}(q - s1)}{\text{Var}(s1 - s2)}, \quad F_2 = \frac{\text{Var}(q - s2)}{\text{Var}(s1 - s2)}, \quad (2)$$

where $\text{Var}(q - s1)$, $\text{Var}(q - s2)$ and $\text{Var}(s1 - s2)$ are the variances of the quasar-star1, quasar-star2 and star1-star2 DLCs, respectively. These F values are then compared individually with the critical F value, $F_{\nu_{QS}\nu_{SS}}^{(\alpha)}$, where α is the significance level set for the test, and ν_{QS} and ν_{SS} are the degrees of freedom of the quasar-star and star-star DLCs, respectively. The smaller the α value, the more improbable that the result is produced by chance. Thus values of $\alpha = 0.0001$, 0.001 or 0.01 (the last assumed in our analysis) roughly correspond to 5σ , 3σ or a 2.6σ detections, respectively. If F is larger than the critical value, the null hypothesis (i.e., no variability) is discarded. Here we also note that having two F -values, F_1 and F_2 , allows us two choices in deciding the presence of variability: (i) to take the average of F_1 and F_2 , and compare it with critical F value; (ii) to compare F_1 and F_2 separately with the critical F value. We prefer the latter option, as it serves as further validation for the F -test; for if one DLC indicates variability and one doesn't, these mixed signals bring into question the reality of the putative variability.

4.2.3 Scaled F -test statistics

Although the F -test is certainly better than the C -test, it should be noted that for the F -test to give a truly reliable result the error due to random noise in the quasar-star and star-star DLCs should be of a similar order, apart from any additional scatter in the quasar-star DLC due to possible QSO variability. For instance, if both comparison stars are either brighter (fainter) than the monitored quasar, then a false alarm detection (non-detection) is possible due to the very small (large) photon noise variance of the star-star DLC compared to the quasar-star DLCs. This in practice can happen, as sometimes it is difficult to fulfill the desiderata of having non-variable comparison stars within the quasar CCD image frame that are very similar in magnitude to the QSO.

In our sample we have tried to choose non-variable comparison stars in proximity to the magnitude of the quasar (see Sect. 4.1), but it was not possible to fulfill this requirement for all quasars. So sometimes in performing the F -test we may have to compare the variance of star-star DLCs involving stars substantially brighter than the quasar, where scatter due to photon noise is very small, with the noisier quasar-star DLC. In such cases, the standard statistics of the F -test do seem to give too much weight to even very nominal fluctuations in a quasar-star DLC. A sensible way to deal with this real problem is to scale the star-star variance by a factor, κ , which is proportional to the ratio of the noise in the quasar-star and star-star DLCs. One logical choice along these lines is to consider the ratio of the average squared error in the quasar-star and star-star DLCs i.e.,

$$\kappa = \left[\frac{\sum_{i=0}^N \sigma_{i,err}^2(q-s)/N}{\sum_{i=0}^N \sigma_{i,err}^2(s1-s2)/N} \right] \equiv \frac{\langle \sigma^2(q-s) \rangle}{\langle \sigma^2(s1-s2) \rangle}, \quad (3)$$

where $\sigma_{i,err}^2(q-s)$ and $\sigma_{i,err}^2(s1-s2)$ are, respectively, the errors on individual points of the quasar-star and star-star DLCs, as returned by the DAOPHOT/IRAF routine. Then the scaled F -value, F^s , can be computed as,

$$F_1^s = \frac{\text{Var}(q-s1)}{\kappa \text{Var}(s1-s2)}, \quad F_2^s = \frac{\text{Var}(q-s2)}{\kappa \text{Var}(s1-s2)}. \quad (4)$$

Here scaling the variance of the star-star DLC by κ basically amounts to normalizing the variance of the DLC by the mean of the squared errors of its individual points (i.e., by $\langle \sigma^2 \rangle$ in Eq. 3). This is sensible, as we know that for no intrinsic variability present in a light curve, the variance gives an estimate of the square of the mean errors (i.e., $\langle \sigma^2 \rangle$) of the light curve. These $\langle \sigma^2 \rangle$ s of the light curves depend on the brightnesses of the observed objects, so to remove any effects of brightness on the variances (used in the standard F -test as $\text{Var}(q-s1)/\text{Var}(s1-s2)$) of light curves it should be better to use the variances that have been normalised by their $\langle \sigma^2 \rangle$ values.

The value of scale factor, κ , used in the *scaled* F -test (Eq. 4) will be near unity if the quasar and stars are of similar magnitude, and as a result it will give a similar F -value as is given by the standard F -test (see Eq. 2). On the other hand, if both comparison stars are either brighter (fainter) than the monitored quasar, then κ will be larger (smaller) than unity. As a result, κ will reasonably scale the variance of comparison star-star DLCs for any magnitude difference between stars and quasar, and hence avoid the problem with the standard F -test which does seem to give too much weight to even very nominal fluctuations in a quasar-star DLC, when it is compared to brighter star-star DLCs.

Other alternatives to the standard F -test are the use of one-way analysis of variance (ANOVA) or a χ^2 test (e.g., de Diego 2010). For an appropriate use of ANOVA the number of data points in the DLC needs to be large enough so as to have many points in each subgroup used for the analysis; however, this is not possible for our observations as we typically have only around 30 data points in our light curves. For the appropriate use of a χ^2 test, the errors of individual data points need to have Gaussian distributions and those errors should be accurately estimated. It has been claimed in the literature that errors returned by photometric reduction routines in IRAF and DAOPHOT usually are underestimated, often by factors of 1.3–1.75 (Gopal-Krishna et al. 2003; Sagar et al. 2004; Bachev et al. 2005), which makes the use of a χ^2 test less desirable for such real photometric light curves. However, as our scale factor depends on the ratio of average squared errors, this possible caveat does not affect our scaled F -test analysis.

In conclusion, we propose that by applying such scaling to the variance of the star-star DLC we can perform a *scaled* F -test, where our scale factor is designed so that it: (i) takes care of the difference in magnitude between the QSO and star in quasar-star and star-star DLCs; (ii) retains the requirement that both the variance being compared in a F -test should have a χ^2 distribution, which is not the case in C -statistics; and (iii) cancels out the problem of uncertain error underestimation by DAOPHOT/IRAF routines reported by many other authors, in that our scaling factors depend on ratios of averaged squared errors. Therefore we report our final results based on this scaled F -test. However it is also worthwhile to compute C -values and standard F -values to facilitate the comparison of results for variability based on them with those based on our newly proposed *scaled* F -test.

Table 3. Microvariability observations of BALQSOs.

QSO	N	T	C-test	F-test				Variability? ^a			$\sqrt{\kappa}^b$	$\sqrt{\langle \sigma_{i,err}^2 \rangle}$
(1)	(2)	(hr) (3)	C-value (4)	F_1, F_2 (5)	F_1^s, F_2^s (6)	$F_C(0.95)$ (7)	$F_C(0.99)$ (8)	C-test (9)	F-test (10)	F_{β} -test (11)	(12)	(Q-S) (13)
WFM91 0226–1024	31	4.04	2.20, 2.47	4.84, 6.10	1.80, 2.25	1.84	2.39	Pv,Pv	V,V	Nv,Pv	1.64	0.02
J073739.96+384413.2	40	5.54	1.45, 1.83	2.11, 3.35	1.73, 1.78	1.70	2.14	Nv,Nv	Pv,V	Pv,Pv	1.24	0.01
J084044.41+363327.8	33	3.86	1.24, 0.84	1.54, 0.71	1.02, 0.51	1.80	2.32	Nv,Nv	Nv,Nv	Nv,Nv	1.21	0.01
J084538.66+342043.6	32	3.90	1.89, 1.99	3.57, 3.96	1.07, 1.08	1.82	2.35	Nv,Pv	V,V	Nv,Nv	1.87	0.01
J090924.01+000211.0	33	3.50	1.74, 1.56	3.04, 2.44	2.35, 1.25	1.80	2.32	Nv,Nv	V,V	V,Nv	1.27	0.02
J094443.13+062507.4	25	2.79	1.37, 1.65	1.87, 2.71	2.80, 2.05	1.98	2.66	Nv,Nv	Nv,V	V,Pv	0.98	0.01
J094941.10+295519.2	36	3.50	2.17, 1.82	4.71, 3.31	2.56, 1.94	1.76	2.23	Pv,Nv	V,V	V,Pv	1.33	0.01
J100711.81+053208.9	33	3.88	1.49, 1.80	2.23, 3.25	0.46, 0.75	1.80	2.32	Nv,Nv	Pv,V	Nv,Nv	2.14	0.04
J111816.95+074558.1	36	3.74	1.56, 1.73	2.44, 3.00	1.77, 2.58	1.76	2.23	Nv,Nv	V,V	Pv,V	1.13	0.01
J112320.73+013747.4	42	3.48	1.17, 1.21	1.38, 1.47	1.12, 1.47	1.68	2.09	Nv,Nv	Nv,Nv	Nv,Nv	1.05	0.01
J120051.52+350831.6	30	3.86	3.25, 3.24	10.57, 10.50	1.64, 1.64	1.86	2.42	V,V	V,V	Nv,Nv	2.53	0.02
J120924.07+103612.0	39	4.10	3.37, 3.06	11.36, 9.34	2.85, 2.41	1.72	2.16	V,V	V,V	V,V	1.98	0.02
J123820.19+175039.1	30	3.77	1.97, 1.98	3.87, 3.92	0.81, 0.74	1.86	2.42	Pv,Pv	V,V	Nv,Nv	2.24	0.01
J125659.92+042734.3	33	3.84	2.32, 2.20	5.40, 4.84	2.99, 2.68	1.80	2.32	Pv,Pv	V,V	V,V	1.34	0.01
J151113.84+490557.4	66	3.70	1.36, 1.37	1.84, 1.88	1.37, 1.79	1.51	1.79	Nv,Nv	V,V	Nv,V	1.09	0.01
J152350.42+391405.2	43	2.75	1.94, 1.83	3.75, 3.35	1.97, 1.96	1.67	2.08	Nv,Nv	V,V	Pv,Pv	1.34	0.01
J152553.89+513649.1	24	3.00	1.16, 1.12	1.35, 1.25	0.73, 1.05	2.01	2.72	Nv,Nv	Nv,Nv	Nv,Nv	1.22	0.01
J154359.44+535903.2	25	2.90	1.94, 2.01	3.75, 4.05	1.33, 1.64	1.98	2.66	Nv,Pv	V,V	Nv,Nv	1.62	0.02
J160207.68+380743.0	32	4.07	2.12, 2.34	4.50, 5.48	2.01, 2.08	1.82	2.35	Pv,Pv	V,V	Pv,Pv	1.56	0.01

^a V=variable, i.e., confidence ≥ 0.99 ; Pv=probable variable, i.e., 0.95 – 0.99 confidence; Nv =non-variable, i.e., confidence < 0.95 . Variability status values based on quasar-star1 and quasar-star2 pairs are separated by a comma.

^b Here $\kappa = \langle \sigma^2(q-s) \rangle / \langle \sigma^2(s1-s2) \rangle$ (as in Eq. 3), is used to scale the variance of star-star DLCs for the scaled F-test.

5 RESULTS

5.1 Differential light curves (DLCs)

The R-band differential light curves (DLCs) of our sample are shown in Figures 1-3. For each quasar the upper panel gives the star-star DLCs of the two best comparison stars and the two lower panels give the quasar-star DLCs. We first give brief notes on each individual source and then present our results based on all three statistical tests, the *C*-test, the *standard F*-test and the *scaled F*-test. As discussed in the previous section our final results will be based on scaled *F*-test but the results based on the other two tests will facilitate their intercomparisons, allowing us to discuss their relative merits.

5.2 Brief notes on individual sources

5.2.1 [WFM91] 0226–1024

[WFM91] 0226–1024 is a high ionization BAL (HiBAL) QSO, having balnicity index (BI) = 7344 km s^{−1}, and detachment index (DI) = 4.72 km s^{−1} (Weymann et al. 1991). This BALQSO was reported as a normal QSO and earlier photometric monitoring to search for its microvariability over ~ 3.4 hr did not yield any positive microvariability detection (Bachev et al. 2005). Over our observational run of ~ 4 hr a peak in the DLC is apparent by visual inspection. However, due to the rather high error bars in the DLCs, the *C*-test and the *F*-test have indicated this source is a possible variable and variable, respectively. But our scaled *F*-test shows it is not variable; nonetheless as the scaled *F*-test with one standard star has shown it as possible variable, this BALQSO is a prime candidate for additional monitoring. For the remainder of the sources we will not discuss the details of the differences between the different statistical tests, reserving a general discussion for the next subsection.

5.2.2 J073739.96+384413.2

J073739.96+384413.2 is a Low ionization (LoBAL) QSO. We have monitored this source over a span of more than ~ 5 hr. Statistical analysis of its DLC shows it is a probably variable source.

5.2.3 J084044.41+363327.8

Becker et al. (1997) reported the discovery of this unusual LoBAL QSO. A spectropolarimetry study by Brotherton et al. (1997) reveals that it is a highly polarized BALQSO, with the continuum polarization rising steeply toward shorter wavelengths, while keeping a constant position angle in the continuum. This source was observed for ~ 3.8 hours, but no evidence of microvariations were detected in its DLC.

5.2.4 J084538.66+342043.6

The source, also known as CSO230, has a black hole with mass $16.4 \times 10^9 M_{\odot}$, estimated using its H β broad line width (e.g., Yuan et al. 2003). It is HiBAL QSO having balnicity index of 2564 ± 1.17 km s^{−1}, and absorption index (AI) of 4091 ± 1.28 km s^{−1} (Trump et al. 2006). This source has been extensively studied spectroscopically. Barlow et al. (1992) has studied its spectral variability during four epochs over a 17-month time span. They found three distinct levels in the broad absorption lines of Si IV 1397Å and C IV 1549Å. A broad-band monitoring effort during this period showed that the continuum level remained constant to within 10 percent. The source remained non-variable during our observational run of ~ 4 hr.

5.2.5 J090924.01+000211.0

This is a HiBAL, with balnicity index of 71 ± 0.90 km s^{−1} (Trump et al. 2006). This is binary quasar system (Hen-

nawi et al. 2006). We observed this source for ~ 3.5 hr. Statistical analysis of its DLC does not give a good indication of rapid variability according to the scaled F -test.

5.2.6 J094443.13+062507.4

This is LoBAL quasar with balnicity index of 820 ± 0.53 km s $^{-1}$ (Trump et al. 2006). This source was found to be probably variable during the course of our ~ 2.7 hr observation, which makes it a potential source for further microvariability study.

5.2.7 J094941.10+295519.2

This source is a prime candidate for microvariability and an intensive search over a long time span (from 1993–1996) was performed by Gopal-Krishna et al. (2000) in their programme to search for intranight optical variability in RQQSOs. They found evidence of an ~ 0.05 mag probable variation and marginal evidence of ~ 0.03 mag variation over observations lasting 2.5 hr and 4.5 hr, respectively. In addition, Jang et al. (2005) monitored this source for two nights for durations of 3.9 hr and 2.0 hr respectively, but they did not find any sign of variability. Our scaled F -test analysis indicates that it possibly exhibited microvariability during our observation lasting ~ 3.5 hr.

5.2.8 J100711.81+053208.9

This is a HiBAL QSO with balnicity index of 2901 ± 0.88 km s $^{-1}$ (Trump et al. 2006). For this source the quasar-star DLC is a noisier than usual. We did not find any signature of microvariability in its DLC during our observation of ~ 3.8 hr. To reach a firmer conclusion as to its rapid variability this source merits additional observations.

5.2.9 J111816.95+074558.1

PG 11514+081, also known as the “triple quasar”, was the second gravitational lens found (Kristian et al. 1993), to have three components with identical spectra (at a redshift of 1.722). Hubble Space Telescope observations resolved the system PG 11514+081 into four point sources and a red extended lens galaxy (Kristian et al. 1993). The source was observed for ~ 3.7 hr and found to be a probably variable source, which makes it an excellent candidate for future microvariability investigations.

5.2.10 J112320.73+013747.4

Meylan and Djorgovski (1989) reported that this quasar is probably lensed by a galaxy at $z \sim 0.6$. The UV line profile structure found with the International Ultraviolet Explorer in this gravitational lens candidate indicates pronounced BAL structure in the high-ionization resonance lines of O VI 1033Å and N V 1240Å. Michalitsianos et al. (1997) performed a comparison of far-UV spectra, with data separated by nearly 10 months, that indicated that changes occurred in both absorption and ionization levels associated with BAL structure in the QSO. We found this source to be non-variable during our ~ 3.4 hr observation.

5.2.11 J120051.52+350831.6

This source is a HiBAL with a balnicity index of 4600 ± 2.48 km s $^{-1}$ (Lamy et al. 2004). This source did not show any significant microvariation over an observational run of ~ 3.8 hr and is non-variable according to the scaled F -test. Although the C -statistic showed it as a strong contender to have presented microvariability, that result appears to have been induced because of its relatively bright comparison stars, as discussed above.

5.2.12 J120924.07+103612.0

Significant variations were noticed in the DLC over our observational run of ~ 4 hr. Note that a coherent variability trend can be seen in both the quasar–star DLCs. Statistical analyses using the C -test, F -test and scaled F -test all strongly indicate the presence of microvariability.

5.2.13 J123820.19+175039.1

This LoBAL is in the Large Bright Quasar Survey, and was also detected in the Chandra BAL quasar survey (Green et al. 2001). We did not find any signature of microvariation in its DLC over an observational period of ~ 3.77 hr.

5.2.14 J125659.92+042734.3

This source has been extensively studied for optical microvariability. Barbieri et al. (1984) did not find any signature of variability in their observations. In their search for intranight optical variability in RQQSOs, Gopal-Krishna et al. (2000) observed this source twice for 5 hr each time and on one of those nights, during which they had unfortunately sparse sampling, saw a hint of microvariation. We have investigated this source for ~ 3.8 hr, and the statistical analysis of its DLCs showed clear evidence of microvariability.

5.2.15 J151113.84+490557.4

This LoBAL quasar has a balnicity index of 802 ± 1.33 km s $^{-1}$ (Trump et al. 2006). We observed this source for ~ 3.5 hr but found no overall evidence of microvariability, although one star-QSO DLC was nominally variable.

5.2.16 J152350.42+391405.2

This is a LoBAL QSO having a balnicity index of 7147 ± 1.66 km s $^{-1}$ (Trump et al. 2006). This bright quasar was found in the third Hamburg Quasar Survey (Hagen et al. 1999). This source appeared to be variable in a 20 cm radio study (Becker et al. 2000). We found it to be probably variable over the course of an observing run of 2.7 hr.

5.2.17 J152553.89+513649.1

This source, also known as CSO 755, is a strongly polarized (~ 3.9 per cent) BALQSO (Glenn et al. 1994). A strongly polarized continuum and unpolarized emission lines indicate that its polarization arises by scattering very near the central source (Glenn et al. 1994). XMM-Newton spectroscopy

of this luminous quasar gives a photon index of $\Gamma = 1.83^{+0.07}_{-0.06}$ and a flat (X-ray bright) intrinsic optical-X-ray spectral slope of $\alpha_{ox} = -1.51$ (Shemmer et al. 2005). The source shows evidence for intrinsic absorption, having a column density of $N(\text{H}) \sim 1.2 \times 10^{22} \text{ cm}^{-2}$. This is among the lowest X-ray columns measured for a BALQSO (Shemmer et al. 2005). We detected no signature of microvariability over a short run of ~ 2.9 hr.

5.2.18 J154359.44+535903.2

J154359.3+535903 is also known as SBS 1542+541 as this source was discovered in the Second Byurakan Survey (Stepanyan et al. 1991). It has many interesting properties: its BAL has a very high degree of ionization (Telfer et al. 1998), an associated absorption system and damped Ly α (DLA) absorption system, and a strong X-ray absorption (Green et al. 2001). This bright high-redshift HiBAL QSO ‘has very highly ionized BALs (including O VI, Ne VIII, and Si XII; Telfer et al. 1998) and appears to have an X-ray brightness typical for a non-BAL of its optical luminosity. Bechtold et al. (2002) has found intervening metal absorption systems at $z = 1.41, 0.1558$, and 0.72 along its line of sight. We found this source to be non-variable during our observation of ~ 4 hr.

5.2.19 J160207.68+380743.0

This source was continuously observed for ~ 3.7 hr. We found this as a probably variable source, which makes this source another potentially good candidate for microvariability studies in the future.

5.3 Variability results based on different statistical test

The results of our analysis are summarized in Table 3; we applied both the C -statistic and the scaled F -test, as discussed above (e.g., see Sect 4.2). In the first three columns we list the object name, number of data points (N_{points}) used in the DLC and the duration of our observation. The fourth column lists the pair of C -values based on star1 and star2 (Eq. 1) while the fifth and sixth columns list the pair of F -values in the standard and scaled F -test. Columns 7 and 8, respectively, give F_c for 0.95 and 0.99 confidence levels. Columns 9, 10 and 11 respectively, list the pairs of variability statuses using star1 and star2 based on C -statistics, the standard F -test and the scaled F -test. The status, based on both star1 and star2 are listed separately rather than using their average value so as to impose as additional validation: is the variability status based on individual stars are consistent with one another or not? In these pairs of variable status indicators using a quasar-star DLC, the quasar is marked as variable (‘V’) for a C -value ≥ 2.576 or F -value $\geq F_c(0.99)$, which corresponds to a confidence level ≥ 0.99 . The quasar is marked as ‘probably variable’ (Pv) if the C value of quasar-star DLC is in the range 1.950 to 2.576 or if the F -value is between $F_c(0.95)$ and $F_c(0.99)$. Those sources for which the C -values are less than 1.95, or the F -value are less than $F_c(0.95)$ are marked Non-variable (‘Nv’). Column

12 lists the square root of scaling factor, $\sqrt{\kappa}$, where it is computed by $\kappa = \langle \sigma^2(q-s) \rangle / \langle \sigma^2(s1-s2) \rangle$ (as in Eq. 3), and has been used to scale the variance of the star-star DLCs while computing the F -value in the scaled- F -test. The last column gives our photometric accuracy, $\sqrt{\langle \sigma_{i, \text{err}}^2 \rangle}$ in the quasar-star DLCs, which typically are between 0.01–0.02mag.

As can be seen from Columns 9 – 11 of Table 3 the variability status indicators based on quasar-star1 and quasar-star2 are often not consistent with one another. The importance of our choice to mark the variable status separately based on individual star vs quasar DLCs can be illustrated by taking the example of J094941.10+295519.2. Based on the C -test its DLC with respect to star1 shows it as a probable variable but with star2 as non-variable. The standard F -test terms it as variable based on both star1 and star2 DLCs. However, this QSO’s status using the scaled F -test is variable based on the first star and probably variable using the second star. The average of the scaled F -value for this source comes out to be 2.25, which is just above the critical F -value of 2.23 for 0.99 confidence, and hence it would be classified as a variable source if we used that average criterion. However, an examination the DLC of this source in top right panel of Fig. 2 by eye indicates that there is no variation that can defined coherently by more than 2 points. Therefore, to exclude such questionable variability and to be on the conservative side for unambiguous microvariable detection, only those sources should be termed as variable for which both quasar-star1 and quasar-star2 DLCs mark the source as variable (i.e ‘V,V’ in Table 3). Probably variable sources are taken as those for which either both the status are of probable variable (i.e., ‘Pv,Pv’ in Table 3) or one quasar-star DLC marks it as a probable variable and the other as a variable (i.e., ‘Pv,V’ or ‘V,Pv’ in Table 3). Sources termed as non-variable (‘Nv’) are those for which at least one of the status based on quasar-star1 and quasar-star2 DLC marked them as non-variable (i.e., at least one ‘Nv’ status in Table 3).

Column (9) of Table 3 indicates that the C -statistics shows two sources as variable and four as probably variable. The scaled F -test shows two sources as variable and six sources as probably variable. As we have discussed above (in section 4.2.3), that scaled F -test is better for our work (and probably also better in many observations made by others) than the standard F -test due to differences between the magnitudes of the quasars and their comparison stars. This is also evident from column (10) of Table 3 which shows that the standard F -test would give 13 sources as variable and two as a probably variable, indicating that this test certainly suffers from the problem related to small variances of the brighter star-star DLCs, at least for our sample of BALQSOs.

Although the C -test and the scaled F -test both give two sources as variable, it is not difficult to appreciate the scaled F -test merits over the C -test by taking specific examples. For instance, J120051.52+350831.6 is a BALQSOs with a C -value of 3.25 from quasar-star1 DLC and 3.24 from quasar-star2 DLC, which seems to make it a clear case of INOV detection, particularly since the C -statistic is usually conservative. However, by looking at the DLCs for this source in the top left panel of Fig. 3, it is clear even by eye that: (i) there is likely to have been a random fluctuation (not a coherent one) for the last 9 points of the DLCs; and

(ii) its comparison stars are about 1.5 mag brighter than this quasar, which makes the variance of the star-star DLC very small (due to small photon noise). As a result the C -value will be artificially very high, leading to false detections. This flaw also crops up in the standard F -test, but is eliminated in the scaled F -test which termed this BALQSO as a non-variable source (not even probably variable). Another source, J120924.07+103612.0, has a C -value of 3.37 from the quasar-star1 DLC and 3.06 from the quasar-star2 DLC but these are probably so high because of the ~ 1.2 mag brighter comparison stars; however, this BALQSO also shows a coherent variability trend (even by eye), and is also termed as variable by the scaled F -test. These empirical examples, and the fact that the scaled F -test detects two cases of unambiguous variability in comparison to the C -test which makes only one unambiguous detections (after eliminating the false positive case mentioned above) clearly shows that the scaled F -test, beside being more sensitive than the C -test to small amplitude variability, is also sufficiently robust to eliminate nearly any false alarm detections.

Therefore, finally, we rely on the result given by the scaled F -test, by which we find two unambiguous detections of microvariability in our sample of 19 BALQSOs up to an accuracy of 0.01-0.02 mag (see columns 9, 10, 11 and 13 of Table 3). As a result, our sample shows that about 10-11 per cent of BALQSOs (i.e., 2 out of 19 sources) certainly showed microvariability (at a confidence level of 0.99).

6 DISCUSSION AND CONCLUSIONS

As noted in the introduction, there have been rather extensive examinations of the frequency of optical microvariability for RQQSOs as well as blazars and other RLQSOs. The typical duty cycle (DC) for blazars is 60–65 per cent (e.g., Gupta et al. 2005), while for normal quasars it has been found to be around 20–25 per cent (e.g., Carini et al. 2007). For both these classes the number of sources in each total sample was quite large, so these values should be reasonably reliable, and support the hypothesis that most of these rapid variations arise, or at least are amplified, in the relativistic jets (e.g., Jang & Miller 1995; Gopal-Krishna et al. 2003). The interesting class of radio-quiet BALQSOs was reported to have a 50 per cent DC but this sample had only 6 members (Carini et al. 2007). Therefore, one of the reasons for the difference in DC results could be poor statistics in the previous study and better statistics now with a sample about a factor of three larger. Apart from sample size, some of the difference might be due to differences in the typical length of the observation. As long known, lengthier observations of blazars are more likely to reveal variability (e.g., Carini 1990), which was also later shown to be the case for RQQSOs (Gupta et al. 2005, Carini et al. 2007). Carini et al. (2007) found that RQQSOs that were monitored for about 6-7 hr showed the highest fraction of microvariability, typically around 24 per cent. In the 4 hour observation range, which is where most of our observations fall, less than 10 percent of sources were found to have microvariability. Therefore the fact that we found about 10-11% DC for radio-quiet BALQSOs is in agreement with the results from the literature for other radio-quiet non-BALQSOs indicates that the BAL nature does not have an effect on the presence of microvariability.

In addition, as we discussed in Sections 4.2 and 5.3, this DC fraction also depends on what statistical test has been used to decide on the significance of microvariation (see de Diego 2010 for details). Most of these previous studies have used the C -test, which has been shown recently to be an unreliable and usually too conservative method to detect microvariation, when compared to proper statistics such as the F -test (de Diego 2010). So, to allow comparison with earlier results, we also computed duty cycles (DCs) of BALQSOs in our sample using the C -test, which shows only one out of 19 source as variable (excluding one false detection, as discussed in Sec. 5.3), resulting in a DC of about 5 per cent. As a result the DCs of all classes of AGN may increase if their DLCs are analyzed with the scaled F -test rather than with the usually more conservative C -test, which, for the 4 hour observation range, were reported at less than 10 per cent for RQQSOs (Carini et al. 2007). Therefore, after taking into account the observation length and the dependence on statistical test used, it seems that the DC of radio-quiet BALQSOs is likely to be of a similar value to the DC of non-BAL RQQSOs, but without redoing all past analyzes with the scaled F -test we cannot be certain of this assertion. Apart from this comparison using the C -test, all our final results and conclusions are based on the more reliable scaled F -test (see Sect. 5.3), which gives our new result of an approximately 11 per cent DC for radio-quiet BALQSOs.

The phenomenon of microvariability was first noticed for blazars, and for them microvariability almost certainly arises from a relativistic jet. However, given the lower DCs for RQ AGN it is still unclear if the nature of intranight variability is the same in these objects, or if it arises from processes in the accretion disc itself (e.g., Mangalam & Wiita 1993; Chakrabarti & Wiita 1993), and thus could possibly be used to probe the accretion disc (e.g., Gopal-Krishna et al. 2000 and references therein). Recent modeling suggests that even for RQQSOs, jet based models should be the most efficient way to produce microvariability (e.g., Czerny et al. 2008). Such jet-based models should predict a difference in equivalent widths of emission lines of variable and non-variable sources, as they should be smaller in the former, due to its dilution by jet components. However, recently this hypothesis was shown to be unlikely based on an analysis of spectra of a set of RQQSOs that had already been searched for microvariability (Chand et al. 2010). Some other possibilities include disc based models where variation can be due to: variable hard radiation from near the disc center that is reprocessed into the UV-optical region (e.g., Ulrich et al. 1997); instabilities in the accretion flow itself producing multiple hot-spots (e.g., Mangalam & Wiita 1993); disco-seismological modes within the disc (e.g. Nowak & Wagoner 1991, 1992). In the first case above the variable hard radiation instead may also come from a hot corona above the accretion disc (Merloni & Fabian 2001).

The shortest variability time scale in this scenario can be associated with the light-crossing time, which will be larger for higher central black hole masses (e.g see Bachev et al. 2005). In a scenario with instabilities in an accretion flow, if one assumes that the inner part of the flow operates through an optically thin advective mode, then the border between it and outer thin disc may be good candidate for the region where these instabilities may occur (e.g., Gracia et al. 2003; Krishan, Ramadurai & Wiita 2003). The time

scale may also be associated with the much longer accretion time scale. Observational estimation of such variability time scales could possibly be used to distinguish between above various disc based scenarios. However, for luminous QSOs such as those in our sample that should have black hole masses in excess of $10^8 M_{\odot}$, even the fastest disc based time scale can be a few hours. As our monitoring of each source rarely exceeded 4 hours and was sometimes unevenly sampled, it is not possible for us to obtain reliable estimates of the variability time scales for the minority of variable sources. Therefore we are not able to distinguish between the various disc based scenarios mentioned above, nor can we cleanly distinguish between jet based and disc based models.

Our larger sample (a factor of three improvement) of radio-quiet BALQSOs, aided by more robust detection criteria, have allowed us to conclude that the fraction of radio-quiet BALQSO showing microvariability are about 11% for an observation length of about 4 hr. This new DC of 11% is similar to the usual low microvariability fraction of normal RQQSOs with observation length similar to our observation, though we note those DCs were obtained using the *C*-statistic and not our scaled *F*-test. This similarity in microvariability frequency provides some support for models where radio-quiet BALQSO do not appear to be a special case of the RQQSOs.

Further extension this type of study to radio-loud BALQSOs will be important in obtaining good values for the microvariability percentage for all types of BALQSOs. Such additional observations will also help in understanding that whether we are viewing BALQSOs closer to the disc plane or to the perpendicular to the disc. In the latter case higher DCs are expected assuming that the cause of microvariation is related to the relativistic jet. In addition, to investigate whether and how X-ray and optical microvariability are correlated in BALQSOs, it will be useful to carry out future simultaneous multi-color optical and X-ray monitoring observations (e.g., Ramírez et al. 2010). Finally, to ascertain whether or not such microvariation depends on spectral properties, additional optical and X-ray spectral analyses of the BALQSOs already searched for microvariability could place important constraints on the possible origin of such microvariations.

ACKNOWLEDGMENTS

The help rendered by the observer at the 1.04-m ARIES telescope, Nainital, and technical staff at the 2.01-m HCT CREST is gratefully acknowledged. We would like to thank the anonymous referee for constructive comments on the manuscript.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is <http://www.sdss.org/>.

REFERENCES

- Adelman-McCarthy J. K., et al., 2007, *ApJS*, 172, 634
- Bachev R., Strigachev A., Semkov E., 2005, *MNRAS*, 358, 774
- Barbieri C., Romano G., 1984, *AcA*, 34, 117
- Barlow T. A., Junkkarinen V. T., Burbidge E. M., Weymann R. J., Morris S. L., Korista K. T., 1992, *ApJ*, 397, 81
- Bechtold J., Dobrzycki A., Wilden B., Morita M., Scott J., Dobrzycka D., Tran K.-V., Aldcroft T. L., 2002, *ApJS*, 140, 143
- Becker R. H., Gregg M. D., Hook I. M., McMahon R. G., White R. L., Helfand D. J., 1997, *ApJ*, 479, L93
- Becker R. H., White R. L., Gregg M. D., Brotherton M. S., Laurent-Muehleisen S. A., Arav N., 2000, *ApJ*, 538, 72
- Brotherton M. S., Tran H. D., van Breugel W., Dey A., Antonucci R., 1997, *ApJ*, 487, L113
- Carini M. T., 1990, PhD Thesis, Georgia State Univ.
- Carini M. T., Miller H. R., Noble J. C., Goodrich B. D., 1992, *AJ*, 104, 15
- Carini M. T., Noble J. C., Taylor R., Culler R., 2007, *AJ*, 133,
- Chand H., Wiita P. J., Gupta A. C., 2010, *MNRAS*, 402, 1059
- Chakrabarti S. K., Wiita P. J., 1993, *ApJ*, 411, 602
- Czerny B., Siemiginowska A., Janiuk A., Gupta A. C., 2008, *MNRAS*, 386, 1557
- de Diego J. A., 2010, *AJ*, 139, 1269
- de Diego J. A., Dultzin-Hacyan D., Ramirez A., Benitez E., 1998, *ApJ*, 501, 69
- Elvis M., 2000, *ApJ*, 545, 63
- Ghosh K. K., Punsly B., 2007, *ApJ*, 661, L139
- Gibson R. R., et al., 2009, *ApJ*, 692, 758
- Glenn J., Schmidt G. D., Foltz C. B., 1994, *AAS*, 26, 875
- Gopal-Krishna, Sagar R., Wiita P. J., 1993a, *MNRAS*, 262, 963
- Gopal-Krishna, Wiita P. J., Altieri B., 1993b, *A&A*, 271, 89
- Gopal-Krishna, Gupta A. C., Sagar R., Wiita P. J., Chaubey U. S., Stalin C. S., 2000, *MNRAS*, 314, 815
- Gopal-Krishna, Stalin C. S., Sagar R., Wiita P. J., 2003, *ApJ*, 586, L25
- Goyal A., Gopal-Krishna, Joshi S., Sagar R., Wiita P. J., Anupama G. C., Sahu D. K., 2010, *MNRAS*, 401, 2622
- Gracia J., Peitz J., Keller C., Camenzind M., 2003, *MNRAS*, 344, 468
- Green P. J., Aldcroft T. L., Mathur S., Wilkes B. J., Elvis M., 2001, *ApJ*, 558, 109
- Gupta A. C., Joshi U. C., 2005, *A&A*, 440, 855
- Gupta A. C., Fan J. H., Bai J. M., Wagner S. J., 2008, *AJ*, 135, 1384
- Hagen H.-J., Engels D., Reimers D., 1999, *A&AS*, 134, 483
- Hennawi J. F., et al., 2006, *AJ*, 131, 1
- Hewett P. C., Foltz C. B., 2003, *AJ*, 125, 1784
- Jang M., 2005, *Ap&SS*, 295, 397
- Jang M., Miller H. R., 1995, *ApJ*, 452, 582
- Krishan V., Ramadurai S., Wiita P. J., 2003, *A&A*, 398, 819
- Kristian J., et al., 1993, *AJ*, 106, 1330
- Lamy H., Hutsemékers D., 2004, *A&A*, 427, 107
- Mangalam A. V., Wiita P. J., 1993, *ApJ*, 406, 420

- Marscher A. P., Gear W. K., Travis J. P., 1992, in Valtaoja E., Valtonen M., eds, *Variability of Blazars*. Cambridge Univ. Press, Cambridge, p. 85
- Merloni A., Fabian A. C., 2001, *MNRAS*, 321, 549
- Meylan G., Djorgovski S., 1989, *ApJ*, 338, L1
- Michalitsianos A. G., Falco E. E., Munoz J. A., Kazanas D., 1997, *ApJ*, 487, L117
- Miller H. R., Carini M. T., Goodrich B. D., 1989, *Nature*, 337, 627
- Montagni F., et al., 2006, *A&A*, 451, 435
- Nowak M. A., Wagoner R. V., 1991, *ApJ*, 378, 656
- Nowak M. A., Wagoner R. V., 1992, *ApJ*, 393, 697
- Rabbette M., McBreen B., Smith N., Steel S., 1998, *A&AS*, 129, 445
- Ramírez A., Dultzin D., de Diego J. A., 2010, *ApJ*, 714, 605
- Rani B., Gupta A. C., Joshi U. C., Ganesh S., Wiita P. J., 2010, *ApJ*, 719, L153
- Reichard T. A., et al., 2003, *AJ*, 126, 2594
- Romero G. E., Cellone S. A., Combi J. A., 1999, *A&AS*, 135, 477
- Sagar R., 1999, *Curr. Sci*, 77, 643
- Sagar R., Stalin C. S., Gopal-Krishna, Wiita P. J., 2004, *MNRAS*, 348, 176
- Scaringi S., Cottis C. E., Knigge C., Goad M. R., 2009, *MNRAS*, 399, 2231
- Schneider D. P., et al., 2005, *AJ*, 130, 367
- Schneider D. P., et al., 2007, *AJ*, 134, 102
- Schneider D. P., et al., 2010, *yCat*, 7260, 0
- Shemmer O., Brandt W. N., Gallagher S. C., Vignali C., Boller T., Chartas G., Comastri A., 2005, *AJ*, 130, 2522
- Stalin C. S., Gopal Krishna, Sagar R., Wiita P. J., 2004, *JApA*, 25, 1
- Stepanyan D. A., Lipovetskii V. A., Chavushyan V. O., Erastova L. K., Shapovalova A. I., 1991, *Ap*, 34, 163
- Stetson P. B., 1992, *ASPC*, 25, 297
- Telfer R. C., Kriss G. A., Zheng W., Davidsen A. F., Green R. F., 1998, *ApJ*, 509, 132
- Trump J. R., et al., 2006, *ApJS*, 165, 1
- Ulrich M. H., 1997, *LNP*, 487, 329
- Véron-Cetty M.-P., Véron, P. 2006, *A&A*, 455, 773
- Weymann R. J., Morris S. L., Foltz C. B., Hewett P. C., 1991, *ApJ*, 373, 23
- Yuan M. J., Wills B. J., 2003, *ApJ*, 593, L11